Computational Modeling of Dissolved Gas Transport and Mixing in the Columbia River Basin

Modeling Subgroup

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1 Introduction

The principal goal of the Transboundary Dissolved Gas Work Group is to advocate measures that will lead to reduced levels of total dissolved gas supersaturation (TDG) associated with spill from dams in the Columbia River Basin. By reducing TDG, mortality in the aquatic ecosystem (for example, anadromous and resident fish populations) caused by gas bubble trauma (GBT) may also be reduced. To achieve this goal in a cost-effective manner, a large number of mitigation concepts will have to be examined at a Basin or System-wide scale. These mitigation concepts could include modifications to dam structures as well as dam operations. A System-wide analysis is required because TDG produced at one dam will propagate far downstream from its point of origin.

The exposure of the aquatic life in the ecosystem to TDG is highly dynamic and can vary significantly from one population to another. The cumulative exposure can become even more complex when considering the effects different gas mitigation concepts can have on river flows and dissolved gas distributions. In order to address the complex nature of TDG exposures numerical models of river flows, gas transport, gas mixing, and dynamic gas bubble trauma must be developed. These models will couple flow, TDG production, TDG transport, and a dynamic GBT dose-response model that will provide an estimation of mortality in select aquatic populations.

It is important to understand that because of the dynamic interaction of predator-prey and bioenergetics relationships with water quality hazards that may affect fish behavior, such models can only extrapolate laboratory or controlled mortality data and may not represent all measured trends in aquatic life population parameters in supersaturated waters. Consequently, the best use of these tools will be to perform comparative evaluations of the various gas mitigation concepts.

2 Objectives of the System Models

The system models should provide the capability to achieve the following general objectives:

- perform an integrated assessment of the impacts of total dissolved gas on selected aquatic life the Columbia Basin system
- inform decision makers on the performance of operational and structural dissolved gas abatement alternatives in order to prioritize mitigation activities
- simulate the fate and transport of dissolved gas through the Columbia Basin system
- simulate magnitude and time of exposure of selected aquatic life to simulated total dissolved gas pressure

3 Elements of a Dissolved Gas Modeling Approach and Alternatives Analysis

There are a large number of components in an integrated model of the physical and ecological impacts of TDG in the Columbia Basin. Figure 1 presents a conceptual model of the components and their linkages. In this section we discuss the key elements of a modeling approach that would have to be included in the application of physical and biological models. The physical models must include hydrodynamics (flow), temperature, and dissolved gas. Temperature is needed in order to apply the thermodynamic relationships to calculate dissolved gas pressure from concentrations (Colt, 1984).

Selection of geographic and time scales of interest will have a significant impact on the type of models selected. A Basin-wide model should include all of the main stem Columbia and Snake River as well as tributaries that have hydroelectric projects. However, some issues may need higher spatial resolution and thus may be limited to applications within a single reservoir or to areas just downstream (a few miles) of a project. The models should be unsteady in order to simulate river flows and TDG transport resulting from hourly (or finer) operations changes. Variable spatial resolution will also be needed to accurately simulate conditions near projects or for sensitive habitat locations. For a system-wide application the models must be able to simulate conditions over one or multiple year periods.

General data requirements for the physical models will include the following items:

- Bathymetry – river bottom elevations
- Hydrology – main stem and tributary inflows
- Meteorology – solar radiation, air and dew point temperature, wind speed
- Project operations – hourly spill and turbine flows
- Project Dissolved Gas Production Relationships – existing conditions and for alternatives

River bottom elevations will be needed to define cross-sections for 1D models and cell elevations for 2D models. Examples of bathymetric data currently available in the Lower Columbia and Snake Rivers can be viewed at the following web site: http://terrassa.pnl.gov:2080/DGAS. Hydrologic data in the form of main stem and tributary flows will be needed as well as estimates of temperature and dissolved gas concentration associated with those inflows. The meteorological data will be needed to compute surface heat exchange and apply air-water gas exchange parameterizations. Project operations data will be used to assign flows at each project and as input to relations to compute dissolved gas production as a function of spillway discharge. Dissolved gas production relationships will also be needed for any proposed mitigation alternatives.

Model calibration and verification data will be needed. At a minimum, tailwater and forebay TDG monitoring data are required. Additional TDG data within the reservoirs would be useful to establish lateral and vertical mixing and air-water gas exchange rates.

Once the model(s) have been configured, calibrated, and verified they can then be used to evaluate existing conditions and mitigation alternatives. A large effort may be required to develop the alternatives scenarios. A key part of each alternative analysis will be the hydrologic record (runoff volume and timing) that is used for input to the model. Some individual or sets of alternatives may appear more or less attractive under high or low runoff conditions.

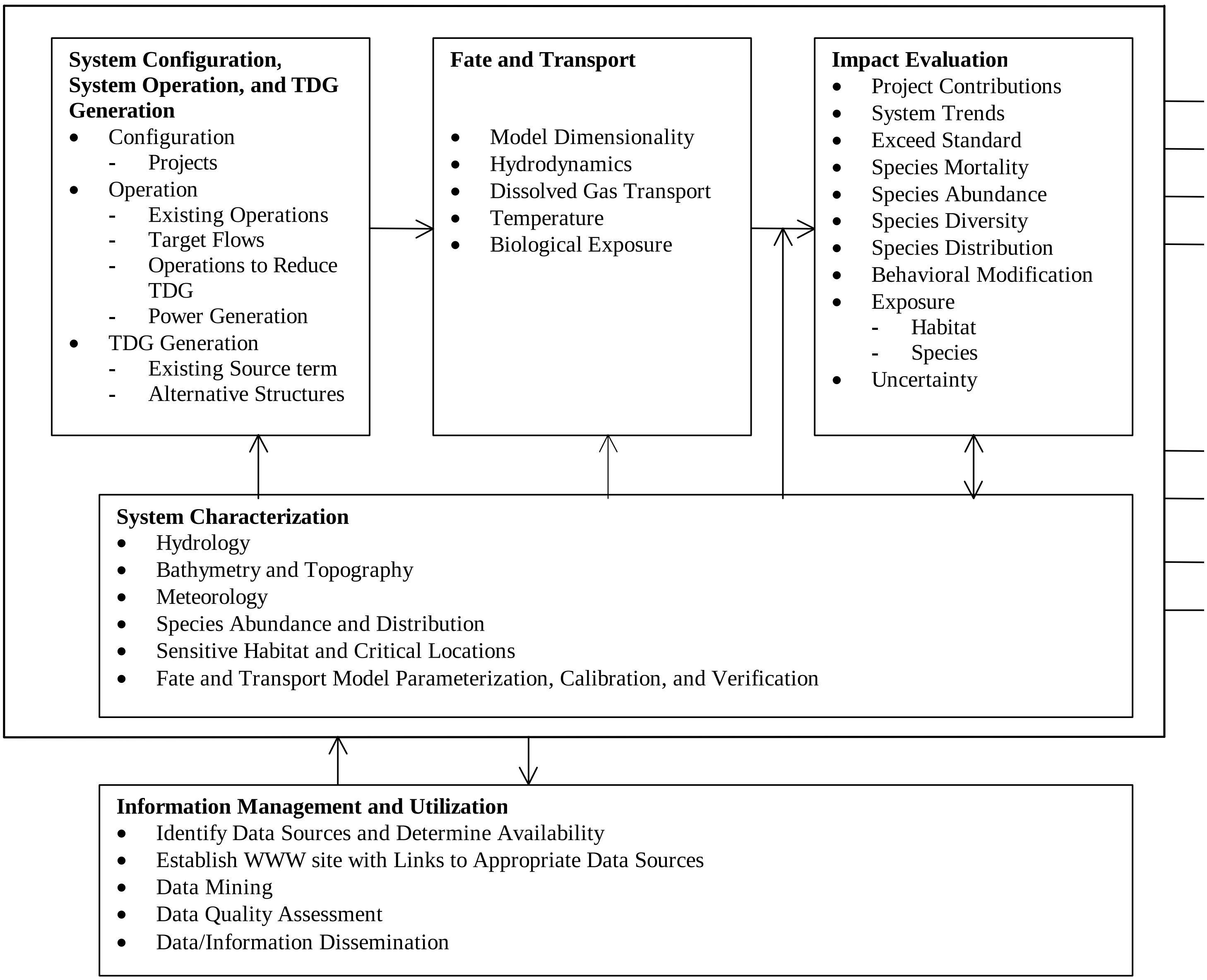

Figure 1. Conceptual Model – Columbia BasinTDG System Modeling

4 Types of Models

A one-dimensional unsteady flow and transport model simulates cross-sectional average values of water surface elevation, discharge, velocity, temperature, and gas concentration. Appendix A summarizes this type of model developed by Richmond and Perkins (1998) and applied to the Columbia and Snake Rivers.

The downstream movement and lateral mixing of dissolved gas produced at each project can be modeled using a two-dimensional (2D depth-averaged) unsteady flow model. The 2D model simulates the depth-averaged (plan view) values of water surface elevation, velocity, temperature, and gas concentration. This type of model can also include the hydro-project (spillway and turbine) gas production relations and then simulate the lateral mixing of the dissolved gas plume across the river. A summary of this type of model developed by Richmond, Perkins, and Scheibe (1998) is presented in Appendix B. Note that this type of model may not be adequate if there are large vertical variations in dissolved gas. In the Columbia and Snake Rivers downstream of Priest Rapids and Lewiston field measurements have shown that vertical dissolved gas variations are small. This may not be the case in deeper reservoirs such as Lake Roosevelt. Width-averaged or three-dimensional models may be needed in such cases to capture vertical dissolved gas distributions.

A GBT dose-response model developed by Fidler (1998) is briefly summarized in Appendix C.

5 Information Gaps

Key physical data needs are:

1. River bathymetry. Initial efforts can use bathymetry estimates from pre-impoundment conditions. This may be sufficient for 1D models. Application of 2D models will require higher-resolution bathymetry.
2. Dissolved production relationships at projects. This is an essential data need for the model.
3. Project Operations. Spillway flows, turbine flows, tailwater, and forebay elevations. These should be in digital form to facilitate use in a computer model.
4. Lateral and vertical variations of dissolved gas in each reservoir.
5. Reservoir specific meteorology.

6 Research Needs

The reliability of the physical models would be enhanced through additional research in the following areas:

- Mechanistic models of gas generation at structures
  The predictive capability of the physical model is directly limited by the accuracy of the input dissolved gas concentration at each project. Ideally, physically based gas production relationships can be developed that would be widely applicable to classes of spillway structures. These relationships would also be required for proposed structural alternatives.
- Statistical Models for gas generation at structures
  In cases where mechanistic models cannot be formulated, statistical models based on field TDG observations will have to be developed.
- Air/water gas exchange parameterizations
  Degassing in reservoirs through air-water gas exchange has been observed to be a significant transport process in the Lower Columbia River. Improved parameterizations in terms of available data (e.g., wind speed and direction) for this process

7 Estimated Level of Effort and Cost

The initial application of a 1D flow and gas transport model using the available data to the entire Columbia Basin would require approximately 1 FTE (FTE = one full-time person for one-year of effort).

Approximately 1 more FTE would be needed to incorporate additional data into the model and perform further verification simulations. The effort required to perform the alternatives analysis would be at least 1 FTE or more depending on the number and type of alternatives that would need to be simulated.

Application of a two-dimensional depth-averaged model would require approximately 0.10 to 0.25 FTEs per reservoir depending on whether the entire or just a part of the pool is included 2D pool effort .

The work to further refine the GBT dose-response model, once the biological research is completed, will take about 1.0 FTE. Applying the model to the existing system would require about 0.2 FTE per pool for two species each.

8 Summary and Recommendations

The initial system-wide assessment model should be a 1D model unsteady flow, dissolved gas transport, and temperature model. The model would be linked to a dynamic GBT dose-response model to assess TDG impacts on the ecosystem. This level of model should provide the means to adequately rank various TDG mitigation alternatives on a system-wide basis. The models can be implemented in a phased approach starting with the best available data and then refined in the future as additional data are collected. For specific reservoirs or river reaches, a depth-averaged 2D model can be applied to assess lateral mixing of TDG plumes when vertical variations of TDG are small. Width-averaged or 3D models may be needed if vertical TDG gradients are significant.

9 References

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10 Appendix A: Unsteady Flow and Water Quality Modeling of the Columbia and Snake Rivers Using the Battelle MASS1 Model

MASS1 (Modular Aquatic Simulation System 1D) is a one-dimensional, unsteady river flow and water quality computer model. MASS1 is being used in several current applications including: transport of radionulcides from past Hanford Site operations, unsteady flow and flood profile analysis of the Hanford Reach, flow and sediment transport in the Lower Snake under natural river conditions (drawdown), and temperature and dissolved gas modeling in the Lower Columbia and Snake Rivers. MASS1 runs on Windows computer systems.

MASS1 simulates a branched river channel system as a set of links and individual points along each link. The model is one-dimensional and is only able to calculate cross-sectional average estimates of hydraulic and water quality conditions in the river and/or reservoir system. For example, only a single, cross-sectional average velocity at a specified river mile is simulated. The model is physics-based; unsteady flow in rivers and canals is simulated by solving the one-dimensional St. Venant equations of mass and momentum conservation.

Standard model output includes the following: discharge, water surface elevation, velocity, temperature, dissolved gas concentration, depth, area, hydraulic radius, channel top width, friction slope, and average shear stress. These outputs can be further analyzed to compute additional information such as water particle travel time and bed shear stress. Users can produce time series plots of water discharge and elevation at a given location or plots of water surface elevation versus river mile at a specific time. All output files are in ASCII format and are easily imported into spreadsheet or plotting programs.

The model domain current extends from the mouth of the Columbia River upstream to Keenleyside Dam in Canada, Dworshak on the Clearwater River, and to Hells Canyon Dam on the Snake River.

11 Appendix B : Two-Dimensional Modeling of Dissolved Gas in the Lower Columbia and Snake Rivers

The U.S. Army Corps of Engineers (USACE) Dissolved Gas Abatement Program (DGAS) is studying options to reduce dissolved gas supersaturation (DGS) associated with federal hydroelectric dams on the Columbia and Snake rivers. In order to address the complex nature of DGS exposures numerical models of gas transport, gas mixing, and dynamic gas bubble trauma are being developed by Battelle, Pacific Northwest Division for the USACE. These models couple hydrodynamics, temperature, DGS production, DGS transport, and fish distribution information with a dynamic gas bubble trauma mortality model which will provide an estimation of cumulative mortality in fish populations passing Columbia and Snake River dams.

The downstream movement and mixing of dissolved gas produced at each project is being modeled using a two-dimensional (2D depth-averaged) unsteady flow and transport model. The model is applied on a pool-by-pool basis to the domain from Lewiston, ID and Kennewick, WA at the upstream boundaries to Portland, OR at the downstream boundary. The 2D model simulates the depth-averaged (plan view) values of water surface elevation, velocity, temperature, and gas concentration. The 2D model will be used to evaluate the details of specific gas abatement alternatives such as changes in spill patterns and the resultant effects on velocities, gas mixing, and fish exposure. These models are physics-based and can be applied to both the current river system configuration and to other alternatives such as natural river configurations.

The model has been applied to several field study periods for each pool. Included herein are example model results for the McNary pool during the summer 1996 study period. Figure 1 shows the comparison between computed and measured depth-averaged velocities at one transect in the area of the Columbia/Snake River confluence. The spatial distribution of dissolved gas saturation is shown in Figure 2. This figure shows the boundaries between the spill/powerhouse water in the Snake River and the Columbia/Snake river water.

The integration of the physical and biological models is done using a model that tracks the space-time position and exposure history for groups of fish (individual exposure model). The FINS (Fish Individual-based Numerical Simulator) model provides a detailed picture of how different gas abatement alternatives affect exposure. FINS works by tracking large numbers of fish groups through each pool as “particles” moving according to user defined rules. The 2D hydrodynamic and transport model provides the required information about the river environment, in this case simulated distributions of velocity, temperature, water depth, and dissolved gas saturation. The space-time position of each fish group is recorded as well as their exposure history to dissolved gas (see Figures 3 and 4). This approach is flexible in that different sets of user defined fish behavior rules can be assigned and directly compared using the same physical setting (velocity, temperature, and dissolved gas). Examples of “fish rules” include relative movement versus water particle movement, differences in day/night movement, species dependent behavior, different depth distributions, and site specific behavioral differences.

Currently, the model has been configured for each pool. The calibration and verification simulations are now complete and the model is now being used to analyze gas abatement alternatives.

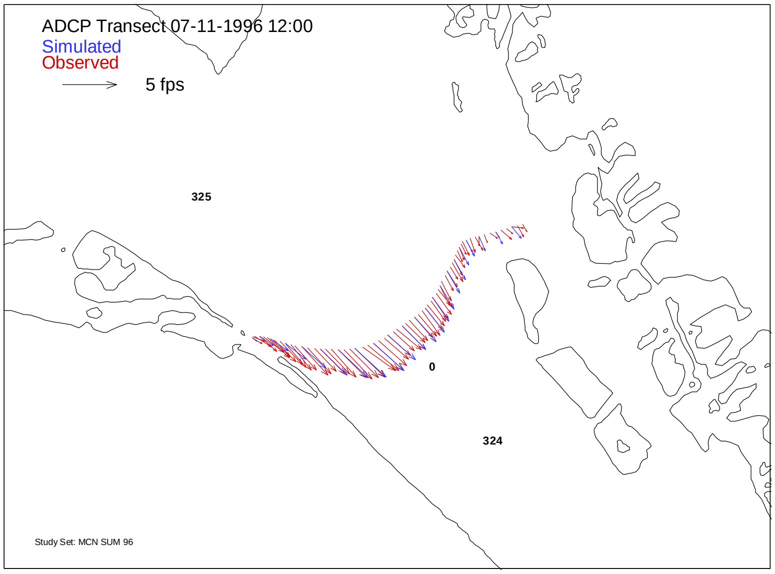

Figure 1. Simulated and observed depth-averaged velocities at the confluence of the Columbia and Snake Rivers on 7-11-1996.

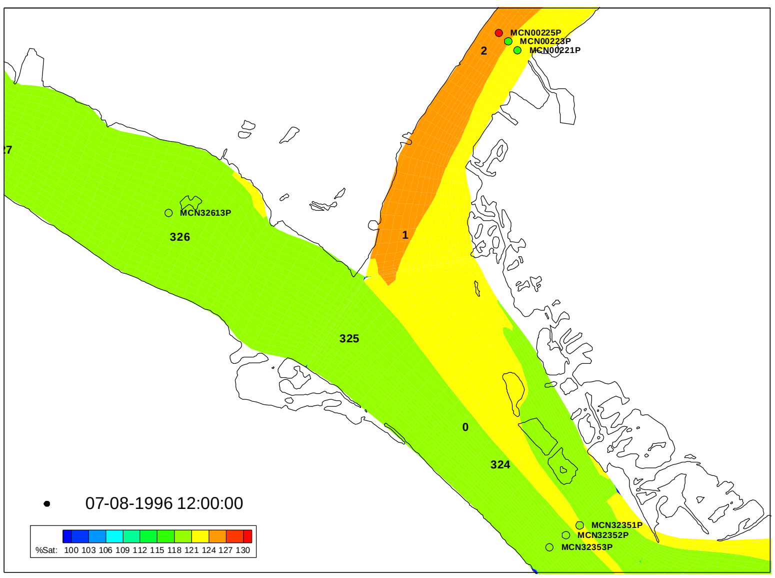

Figure 2. Snapshot of the total dissolved gas distribution at the confluence of the Columbia and Snake Rivers on 7-8-1996. The field monitors (circles) are color coded to their measured saturation.

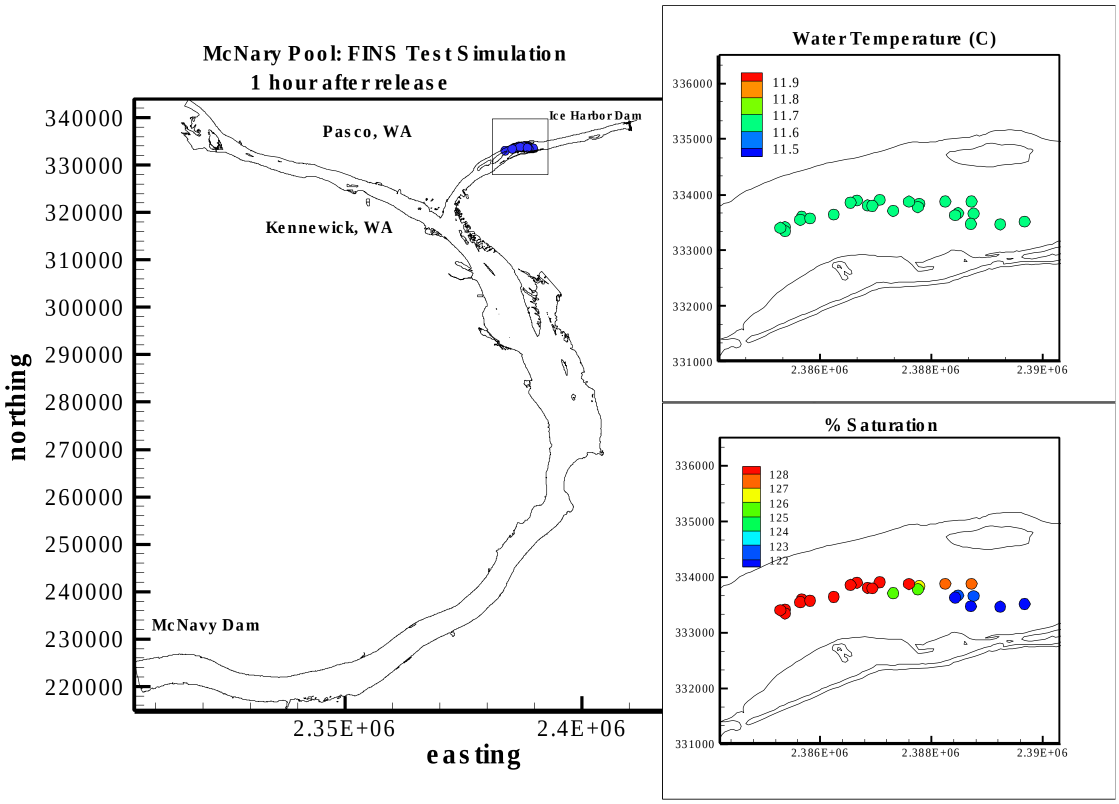

Figure 3. Fish distribution 1 hour after release at Ice Harbor Dam. The fish particles are colored according to the level of dissolved gas exposure at that location.

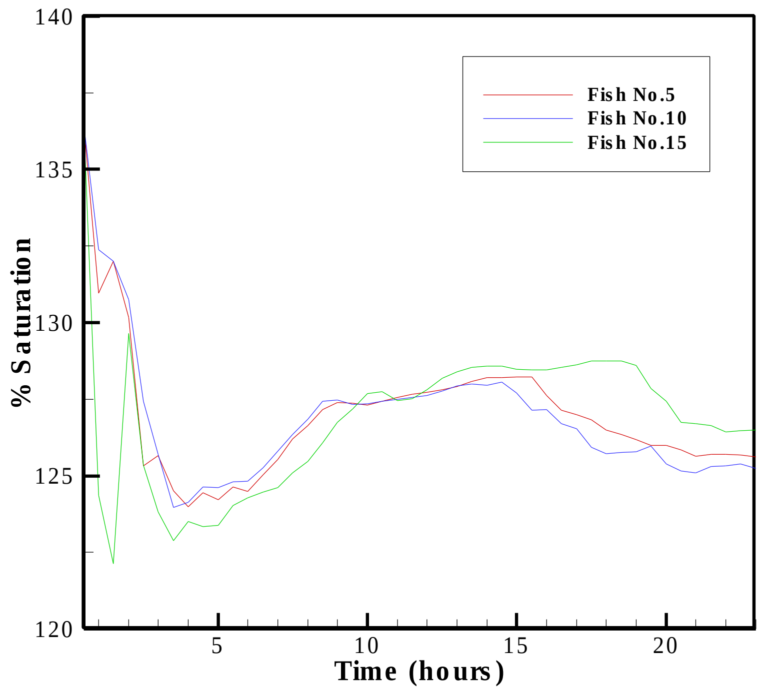

Figure 4. Dissolved gas concentration exposure logs for 3 randomly selected fish.

12 Appendix B: The Dynamic GBT Mortality Model: (DGBTM) Model

In response to the 1994 National Marine Fisheries Service's (NMFS) Biological Opinion, the U.S. Army Corps of Engineers (U.S. ACE) initiated a Gas Abatement Program which is intended to reduce dissolved gas supersaturation (DGS) associated with federal hydroelectric dams on the Columbia and Snake rivers. The reduction of dissolved gas supersaturation may contribute significantly to a lowering of gas bubble trauma (GBT) mortality in anadromous and resident fish populations of these rivers. To achieve this goal, the U.S. ACE is examining a number of design concepts that include modifications to dam structures as well as dam operations. In order to evaluate the effectiveness of the different gas abatement concepts, the relative reduction in GBT mortality in anadromous fish populations has been chosen by the U.S. ACE as one basis for comparing the various concepts. In order to establish the relative reduction in GBT mortality between the various design concepts, the U.S. ACE requires analytical tools that can predict cumulative mortality in fish populations of the Columbia and Snake rivers.

1.0 Background

When describing and analyzing the effects of DGS on fish, it is important to recognize that the signs and consequences of GBT are determined by the exposure history of the fish coupled to the physiological and environmental response of the animal. That is, the effects are expressed in terms of a classic dose - response relationship. In the case of GBT, the dose must include not only the TGP and temperature, but also the depth at which the exposure takes place (Fidler and Miller 1997, Fidler 1998a and b). In defining the dose - response relationship, there are four major components that must be considered. Collectively, these components define and set limits for GBT impacts in any aquatic environment. They include:

1) **The physical environments in which the exposures take place (*i.e.*, the spatial and temporal distribution of TGP and temperature).**
2) **The behaviour of the animal in that environment (*i.e.*, the spatial and temporal position of the fish in the TGP and temperature fields).**
3) **The GBT physiological responses of the animal in terms of cardiovascular bubble growth, emphysema of internal and external tissues, swim bladder overinflation, *etc*.**
4) **The direct and indirect biological consequence of the physiological response including both acute, and chronic effects.**

The first two components define the exposure history or dose, while the third and fourth components define the biological consequences of the exposure. In the remainder of this document, these components are referred to as the GBT Dose - Response Relationship. The dependence between the four components can be expressed in the following form:

Physical Environment + Fish Behaviour ® Physiological Response ® Biological Consequences

However, all four components are highly dynamic and must be integrated over the entire exposure period in order to define the complete GBT impact. Information gaps in any of the four components of the GBT Dose - Response Relationship severely limits the integrity of GBT impact assessments in any aquatic environment.

Other important factors influencing GBT mortality are temperature and swimming activity. Susceptibility to GBT increases with increased temperature (Nebeker *et al.* 1979) and increased swimming effort (Bouck *et al.* 1975). Because dissolved gas exposure can vary with fish migration depths, TGP, temperature, and both water and migration velocities, cumulative exposure is highly dynamic and can differ significantly from one population of fish to another. The cumulative exposure can become even more complex when considering the effects that different gas abatement concepts may have in altering river flows and dissolved gas distributions.

To address the complex nature of TGP, ΔP, and temperature exposures in the Columbia and Snake rivers, Aspen Applied Sciences Inc. developed a dynamic GBT mortality (DGBTM) model to evaluate direct cumulative GBT mortality resulting from a wide variety of possible dissolved gas and temperature exposure scenarios.

When combined with other models that predict river flow characteristics, dissolved gas production, dissolved gas transport, mixing, temperature, and fish distributions, the DGBTM model allows an estimation of cumulative direct GBT mortality in fish populations passing Columbia and Snake River dams. This capability provides the U.S. ACE with one of the key tools needed to perform comparative evaluations and identify those gas abatement concepts that are most effective in reducing the incidence of GBT.

2.0 Cumulative GBT Mortality from Cardiovascular Bubble Gorwth

The DGBTM model has been developed to allow the prediction of cumulative mortality in populations of fish exposed to time varying conditions of TGP, ΔP, and temperature. The model is capable of treating a wide range of fish species and sizes under these dynamic exposure conditions. Although a variety of signs of GBT have been observed in fish exposed to elevated TGP, only overinflation and rupture of the swim bladder in small fish (Shrimpton et al 1990a and b) and the growth of bubbles in the cardiovascular system (Rucker 1975, Nebeker *et al*, 1976, Stroud and Nebeker 1976) have been show to be direct causes of GBT mortality. The DGBTM Model has been developed to analyze direct cumulative mortality from cardiovascular bubble growth. The model was developed around a six-stage process that leads to mortality. The model stages include:

Stage 1: Venous Blood Dissolved Gas Equilibration. This stage accounts for the time required to equilibrate venous blood TGP and ΔP to levels that will allow nucleation sites and bubbles to grow.

Stage 2: DP Threshold for Bubble Growth. For the first exposure of a population of fish to elevated TGP, this stage follows ΔP in the heart and afferent branchial arteries and does not allow bubble growth to begin until the local ΔP exceeds a threshold value.

Stage 3: Cardiovascular Nuclei and Spherical Bubble Growth. This model stage accounts for the growth of nuclei into spherical bubbles in the cardiovascular system of fish exposed to lethal levels of TGP. Specifically, this stage applies to bubbles that form in the sinus venosus and atrium of the heart and migrate with blood flow to the afferent branchial arteries. Once the spherical bubbles grow to the diameter of the afferent branchial arteries, blood flow to the afferent filamental arteries is blocked and tubular bubble growth in the afferent filamental arteries begins.

Stage 4: Tubular Bubble Growth. This stage accounts for the growth of tubular bubbles in the afferent filamental arteries. This stage applies to the first fish in a population to die from GBT.

Stage 5: Time to Initiation of Mortality. This stage regulates the onset of mortality in a population of fish exposed to lethal levels of TGP. It is controlled by the extent of tubular bubble formation in the afferent filamental arteries of the first fish in the population to die from GBT. Fish die from cardiovascular bubble growth only after the afferent filamental arteries are almost completely blocked with tubular bubbles.

Stage 6: Mortality Rate Function. This stage accounts for the rate at which mortality develops in a population of fish over time, once tubular bubbles in the afferent filamental arteries have led to mortality in the first members of the population.

Calibration and validation of the DGBTM model requires a comprehensive set of laboratory physiology data and GBT bioassay data for a range of fish species, sizes, water temperatures, and TGP levels. At present, there are only limited laboratory physiology data available that can be used for calibrating the

DGBTM model and there are bioassay data for only two species of fish of limited size and exposure conditions (see Table below). Using these limited data sets, preliminary calibration of each of the DGBTM model stages has been performed for 117 - 120 mm chinook salmon at 15° C. Only Stages 5 and 6 have been calibrated for 180 mm steelhead trout at 10° C.

Species	**Fork Length mm**	**Sea Level TGP%**	**Temperature**	**Authors**
Steelhead Trout	180 mm	115 and 122	10	Dawley *et al.* 1976
Chinook Salmon	117 - 120	117 and 123	15	Dawley and Ebel 1975

With these preliminary calibrations, the model has been used to predict conditions of cardiovascular bubble growth and mortality in populations of fish exposed to a range of dynamic conditions of TGP, ΔP, and temperature. The exposures correspond to those that might exist for fish migrating between Ice Harbor Dam on the Snake River and McNary Dam on the Columbia River. The example analyses demonstrate the functionality of the DGBTM model and its ability to detect changes in cumulative mortality for very small changes in TGP. This ability is important to the U.S. ACE Gas Abatement Program since some of the design changes to dam spillways that are being considered may result in only small differences in river TGP between different designs. A more complete description of the DGBTM Model, it's development, and calibration can be found in Fidler 1998a and b.

3.0 Model Analysis Operation

The DGBTM Model is a completely operational model that operates in the Microsoft Windows environment. When the user starts the program, the user interface window shown is presented (Figure 1). In the upper left of the window, there is a menu titled "File". By clicking the right mouse button on this menu, a drop down menu is activated which allows the user to "Open" a file or "Exit" the program. By clicking on the "Open" menu, another drop down menu lists the directories of exposure logs that are available. By clicking on a particular directory, a drop down list of the available exposure logs in that directory is presented. The user selects a file name by clicking on it once with the mouse and then clicking on the open button. Double clicking on the file name accomplishes the same thing. At this point, the program loads the file and performs the analysis of bubble growth and mortality. The file that has been loaded in this example is an exposure log corresponding to the data for 117 - 120 mm chinook salmon of Dawley and Ebel (1975). Once the analysis is complete, the program presents the user with a window in which there is an array of titled buttons for each of the parameters relevant to the GBT cumulative mortality calculations. By clicking on a button, the user can see a plot of the variation in that particular parameter over the time of the exposure log. For example, clicking on the TGP button produces a window with the plot showing the variation in water TGP and internal TGP as a function of time. Clicking on the "Fish Depth" button shows a plot where the variation in depth of the fish population is shown as a function of time. Other plots include: the variation in "Delta P" as a function of time, the variation in water "Temperature" with time; the variation of "Bubble Radius" with time for bubbles in the afferent branchial arteries; the variation in afferent filamental artery "Tubular Bubble Length" with time, and the variation in "% Mortality" for the population with time. A text box below the parameter buttons provides a numerical value for the cumulative mortality at a time corresponding to the end of the exposure log. Near the top of the window a text box shows the name of the exposure log that has been processed most recently.

The user has the option of returning to the "File" menu and opening additional exposure logs. As each new log is opened, the same buttons are available to examine "TGP", "Fish Depth", *etc*. The "Running % Cumulative Mortality text box shows the combined % cumulative mortality for all of the files that have been processed previously. This feature allows a wide variety of exposure logs to be analyzed for any given river reach and combined into a cumulative mortality for multiple populations of fish. However, for this feature to be accurate, all exposure logs must begin and end at the same river transect.

4.0 Recommendations

A key requirement of the program is to have the capability of assessing reductions in GBT mortality that can be achieved with the various gas abatement design concepts. At present, the DGBTM model is the only analytical tool that can predict cumulative GBT mortality under the dynamic exposure conditions that exist in the Columbia and Snake rivers. Thus, it is important that the model is completed and brought to a stage of full calibration and validation. To achieve this, a series of laboratory physiology studies and bioassays must be performed. Once the required experimental data are obtained, it will be necessary to map the data into analytic forms, but with the added variables of fish length, temperature, activity level, and the effects of prior exposure to hydrostatic pressure.

In addition to the completion, calibration, and validation of the DGBTM model, there is a need for data on fish behavior in the Columbia and Snake rivers. Fish longitudinal and lateral positions as well as depth play an important role in developing the TGP, ΔP, and temperature exposure histories that are needed to analyze cumulative GBT mortality. Once this behavior is characterized, it can be implemented in the Battelle Fish Particle Tracking computer model (Richmond *et al*. 1998) which, along with the Battelle 2D Transport and Mixing computer model (Richmond *et al.* 1998), generate the exposure logs that are the required input to the DGBTM computer model. Therefore, it is important that in-river studies are implemented in which the longitudinal and lateral positions as well as depth behavior of migrating juvenile Pacific salmon and steelhead trout are monitored and characterized.

The combination of the Aspen Applied Sciences DGBTM mortality model, the Battelle Fish Particle Tracking computer model, and the Battelle 2D Transport and Mixing computer model provide a computational framework that can be expanded to include other environmental and biological parameters that affect migratory and resident fish survival in the Columbia and Snake rivers. For example, the effects of elevated water temperature on predation, disease, and reduced swimming capacity on the survival of fish populations can be easily built into these models. As well, the effects of acute and chronic lethal temperature limits can be incorporated into the models. The effects of exposure to elevated TGPs, temperatures, and swimming demands on the survival of migrating adult Pacific salmon and steelhead trout can also be added to the models. The models can be expanded to include the effects of all of the above environmental and biological parameters on the survival of resident fish in the Columbia and Snake rivers. Clearly, there is a wide range of predictive benefits that can be derived by including in these models an expanded array of environmental and biological parameters that affect fish survival. Therefore, it is recommended that additional studies be undertaken to incorporate these parameters into the Aspen Applied Sciences DGBTM model, the Battelle Fish Particle Tracking computer model, and the Battelle 2D Transport and Mixing computer model.

Once the DGBTM model is fully calibrated and fish behavior is characterized, the combination of models can be used to address not only the requirements of the U.S. ACE Gas Abatement Program, but a wide variety of other applications as well. For example, the program can be used as a management tool to evaluate decisions regarding river flow management and spill. In other situations, the program can be used to identify TGP, GBT, temperature and predation "biological hot spots" in the Columbia and Snake rivers. The DGBTM model can also be used to analyze TGP, GBT, temperature, predation, and disease problems in the mid- and upper-Columbia River, the Columbia River in Canada, and the Kootenay River. In addition, there are many rivers throughout North America as well as in foreign countries where hydroelectric dams and power plant effluents have produced problems of elevated TGP and temperature (*e.g.* the Missouri, Tennessee, and Big Horn rivers of the U.S.A., the Stave and Mactaqua rivers of Canada, the Piranha River of Uruguay). There are rivers in which elevated TGP and temperature are problems even without the presence of hydroelectric dams (*e.g.*, the Fraser River of British Columbia). All of these situations can be analyzed with both the present as well as expanded versions of the integrated Aspen Applied Sciences DGBTM model, the Battelle Fish Particle Tracking computer model, and the Battelle 2D Transport and Mixing computer model.

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Figure 1: Opening User Interface Window for DGBTM Model